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OFFICE MEMORANDUM

TO : H. Murphy

DATE: July 10, 1981

FROM : J. W. Tester and C. O. Grigsby

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SUBJECT : FRACTURE VOLUME GROWTH AND FLUID MIXING IN THE PHASE I SYSTEM

SYMBOL : G-5

MAIL STOP: 981

A complete review of the tracer test data from Segments 2 through 5 has revealed pertinent information regarding the growth of the reservoir. Several parameters have been correlated with observed changes in the flow through reservoir volume as measured by both sodium fluorescein and bromine (Br^{82}) tracers. These include the effects of thermal energy removal, pressurization including massive hydraulic fracturing, and wellbore separation distance on the reservoir volume. Ultimately, we would like to correlate measured tracer volumes with effective heat transfer surface. In addition, the interpretation of tracer volume changes could be used to develop improved methods of reservoir operation -- for example, remedial pressurization for stress relief (like SUE) or a huff-puff operation mode in contrast to our normal (stress-constrained) continuous mode of extracting heat.

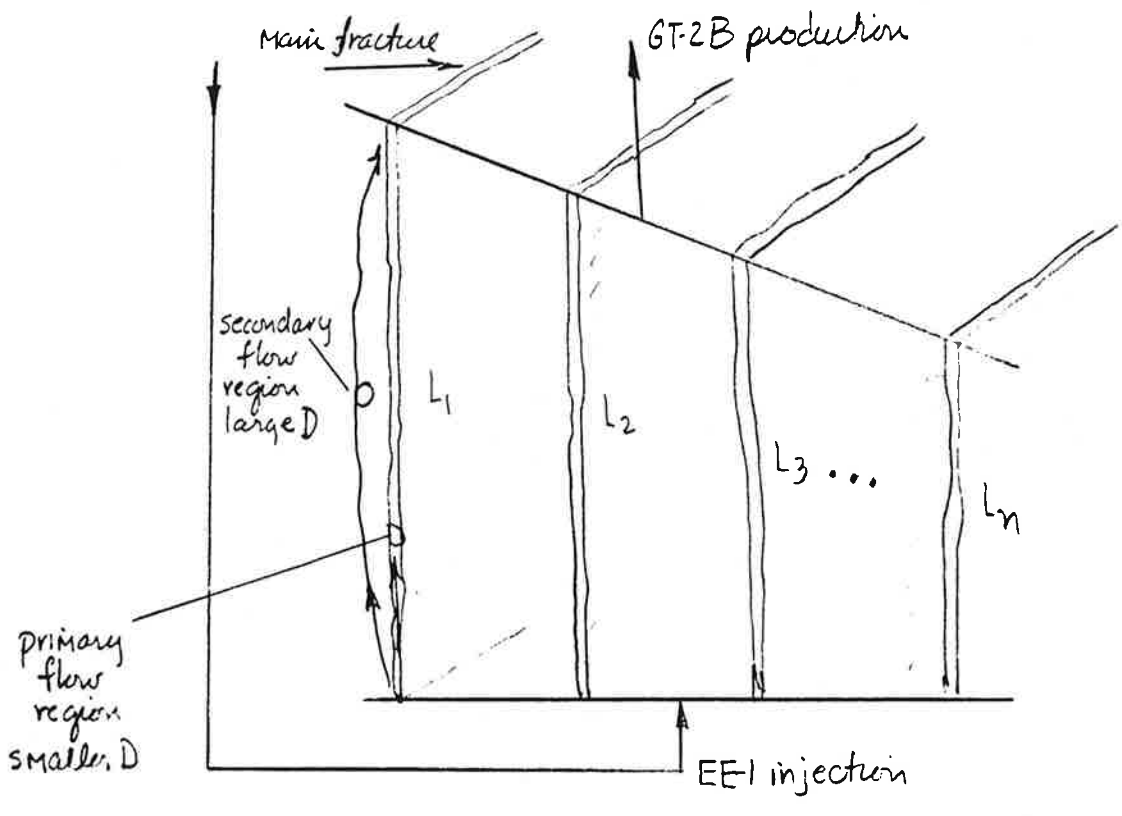
Table 1 provides the complete set of tracer results and reservoir conditions for Segments 2 through 5. Three important observations fall out of a preliminary analysis:

1. The flow is well-mixed in all cases with a large level dispersion.

2. The measured flow-through volumes (modal, integrated mean or median) show a distinct growth as thermal energy is extracted from the reservoir.

3. The increase in measured volume also correlates with the observed growth in effective heat transfer area between the original and enlarged phase 1 reservoirs.

The first observation of well-mixed flow is a result of the superposition of dispersed flow in discrete fractured regions of variable mean residence time. This behavior has been characterized by the downhole Br^{82}, spinner, and temperature logs. In addition, the level of dispersion in each fractured region is probably caused by macroscopic convective mixing effects induced by the rough surfaces of the main fractures themselves and by microscopic dispersion from a region of secondary cracks adjacent to the main crack flow paths. This latter region can be adequately represented by either a uniform highly dispersed flow path or by a continous distribution of residence times in a region of variable aperture. The flow model is schematically shown below:



Main fracture length variations (L_i's) superimpose localized dispersion effects within and around the main fractures to yield the observed residence time distribution for the tracer. This behavior does suggest that we can approach a more effective method of heat mining by inducing a level of volumetric sweep away from the main fracture flow path. In addition, it may have some extremely beneficial effects in regard to potential solution mining of strategic resources.

Figures 1 and 2 introduce the second and third important observations from the tracer tests, namely that the reservoir grows in size (volume and area) as heat is extracted and/or as access is gained to other dormant high impedance regions by hydraulic pressurization during fracturing. Data for low and high back pressure operation of the original and enlarged reservoirs are shown. Figure 1 is a linear plot of modal volume increase (ΔV) as a function of net thermal energy extracted from the reservoir (ΔE) while Figure 2 shows the same data on a logarithmic scale. Essentially identical linear behavior is observed for the low pressure, 75 day test (Segment 2) of the original reservoir and the low pressure, 280 day test (Segment 5) of the enlarged system. In spite of the non-linear coupled effects of thermal contraction, pore and fracture inflation due to sustained pressurization, and local irreversibilities resulting in fracture propagation, a simple correlation between ΔV and ΔE exists. Furthermore, this simple relationship persists even in the presence of the confining stresses surrounding the active reservoir which induce a constrained behavior. The slope of the line for low back pressure operation is only about 10% of what would be expected for free thermal expansion ($\Delta V = [\alpha_v/\rho C)_r]\Delta E$) in a stress free environment. Values of $\alpha_v = 24 \times 10^{-6}\ K^{-1}$, $C_r = 1000$ J/kgK and $\rho = 2700\ kg/m^3$ were used to represent the granite matrix. For all practical purposes, the region between the low pressure data and the free thermal volume lines defines an envelope of reservoir operating conditions. As stresses are relieved, for example during the stress unlocking experiment (SUE) at the end of Segment 5, the high back pressure test of the original reservoir (Seg. 3), or the Massive hydraulic fracturing test (MHF) at the beginning of Segment 4, one moves away from the normally constrained condition toward the free thermal volume line.

Perhaps the most promising aspect of the tracer tests is their potential for estimating the effective heat transfer surface area of a reservoir. On a preliminary basis, areas resulting from fits to observed thermal drawdown can be correlated to changes in either the modal, mean, or median volumes. Using the modal volume as the most characteristic parameter for main crack flow, fracture apertures of a few millimeters result. This seems reasonable when surface roughness effects are included to estimate fracture flow impedances. Consequently, if similar aperture profiles are assumed for main and secondary fractures in the original and enlarged reservoirs tracer volumes should correlate directly with active heat transfer area. Figure 3 shows the expected correlation. By developing these empirical correlations further, tracer methods should provide a direct and independent method of determining reservoir heat transfer areas without requiring thermal drawdown.

xc:

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TABLE 1. Summary of Fluorescein Dye and Br^{82} Tracer Experiments in the Phase 1 EE-1/GT-2B Fracture Systems

Experiment	Elapsed days	P^{g}_{EE-1} MPa	P^{g}_{GT-2} MPa	$\dot{Q}$ $10^3 m^3$	$\dot{q}_{GT-2}$ $10^{-3} m^3/s^b$	$C_f V_f$ tracer feed 10^4(ppm) liters	(c) $\dot{q}_{loss}$ 10^{-3} m^3/s	Tracer recovery %	Average fluid production temp. °C	Mean $\langle V \rangle$ m^3	Median [V] m^3	90% Trimmed mean $\lvert V \rvert$ m^3	Variance σ^2_θ	Variance σ^2_θ (90%)	(d) Pe^{*-1}	Mode $\overset{\circ}{V}$ m^3	Total fluid vol. measured during tracer test	Incremental Thermal energy extracted 10^{12}J	$\overset{\circ}{V}_{t=0}$ m^3
ORIGINAL RESERVOIR																			
Segment 2 (75 day)																			
Phase 1-1 (2/9/78)	8	8.8	1.1	8.0	7.25	7.57	1.30	69	150	34.4	25.6	29.3	0.65	0.44	0.591	11.4±1.1		2.29	
Phase 1-2 (3/1/78)	28	8.5	1.1	26.1	13.1	7.57	0.60	65	110	37.5	28.9	30.9	0.62	0.43	0.942	17.0±1.5		7.16	10
Phase 1-3 (3/23/78)	50	6.6	1.1	57.2	13.9	7.57	0,75	71	95	54.7	45.1	46.3	0.51	0.42	0.944	22.7±2.3		12.90	
Phase 1-4 (4/7/78)	65	5.9	1.1	75.7	15.5	7.57	0.18	>65	90	56.2	48.4	49.2	0.47	0.39	1.120	26.5±2.7		16.40	
Segment 3 (28 day)																			
Phase 1-5 (9/28/78)[i]	10	9.3	9.7	9.0	7.7	7.57	3.17	60	111	33.1	24.7	26.6	0.75	0.56	0.358	$3.8^{+5.7}_{-1.9}$		1.01	
Phase 1-6 (10/13/78)[h]	25	9.3	9.7	26.3	9.3	11.36	3.17	74	98	56.5	46.5	48.1	0.45	0.36	0.306	11.4±1.5		3.36	2.5
Phase 1-7 (10/16-78)[k]	28	9.3	1.7	∿30.0	15.7	11.36	4.28	33[e]	-	49.6	40.5	41.8	0.49	0.38	0.347	20.8±1.9		3.70	
ENLARGED RESERVOIR																			
Segment 4 (23 day)																			
215-1 (10/26/79)	-	17.2	1.1	1.3	6.4	11.36	8.70	13(25)[f]	153	207.	192.	184.	0.26	0.22	0.195	136. ±19	469	-	
215-2 (10/29/79)	0	17.2	10.3	6.1	8.1	11.36	14.00	18	154	230.	211.	209.	0.17	0.12	0.360	144. ±19	619	-	120
215-3 (11/2/79)	2	9.3	1.1	9.5	6.6	45.42	1.13	27	153	262.	216.	243.	0.38	0.34	0.281	121. ±11	570	0.37	
215-4 (11/12/79)	12	9.3	1.1	16.2	6.4	45.42	1.27	25	153	283.	236.	263.	0.32	0.28	0.310	129. ±11	662	2.24	
Segment 5 (282 day)																			
217-A1 (4/16/80)	38	9.8	1.3	13.1	6.2	45.42	0.90	>57	158	404.4	341.1	500.	0.45	.44	0.760	155. ±10	1440	5.9	
217-A2 (5/9/80-Br)[j]	61	9.5	1.3	26.5	5.9	38.4mCi[l]	0.50	-	158	1100.	1072.	941.	0.53	0.52	-	161. ±4	3030	9.9	151
217-A3 (9/3/80-Br)	178	8.8	1.3	74.0	5.7	383.0mCi	0.38	-	154	1311.	1245.	1274.	0.56	0.54	-	178. ±4	4140	27.1	
PreSUE 217-A4 (12/2/80-Br)	268	8.5	1.1	121.0	5.1	519.0mCi	2.30[o]	-	149	581.[n]	541.	525.	0.40	0.38	-	187. ±10	1310[n]	39.9	
PostSUE 217-A5 (12/12/80-Br)	278	8.4	1.3	126.0	8.1	377.0mCi	0.90[o]	-	149	1118.[n]	965.	1009.	0.46	0.42	-	266. ±4	2690[n]	41.2	

a 1 gal = 3.785 liters = 3.785 x $10^{-3}m^3$
b 1 gpm = 6.31 x 10^{-2} liters/s = 6.31 x 10^{-5} liters/s
c includes diffusional loss and leaks
d $Pe^{*-1} = D/u\ell$ = inverse dispersional Peclet number for single 1-D zone fit
e spectrophotometer error possibly explains low recovery
f 25% recovered after switch to high backpressure in GT-2B
g surface pressures not buoyancy corrected

h volume correction added 7.344 m^3 (1940 gal) to eliminate negative volumes (early arrivals)
i volume correction added 3.937 m^3 (1040 gal) to eliminate negative volumes (early arrivals)
j tracer used Br^{82} in place of Na-fluorescein
k 10/26/78 test actually during exp. 190 at LBP
l millicurie (mCi) strength of feed at injection
m corresponds to first arrival of tracer
n exp. terminated before tail of distribution
o includes annulus leak

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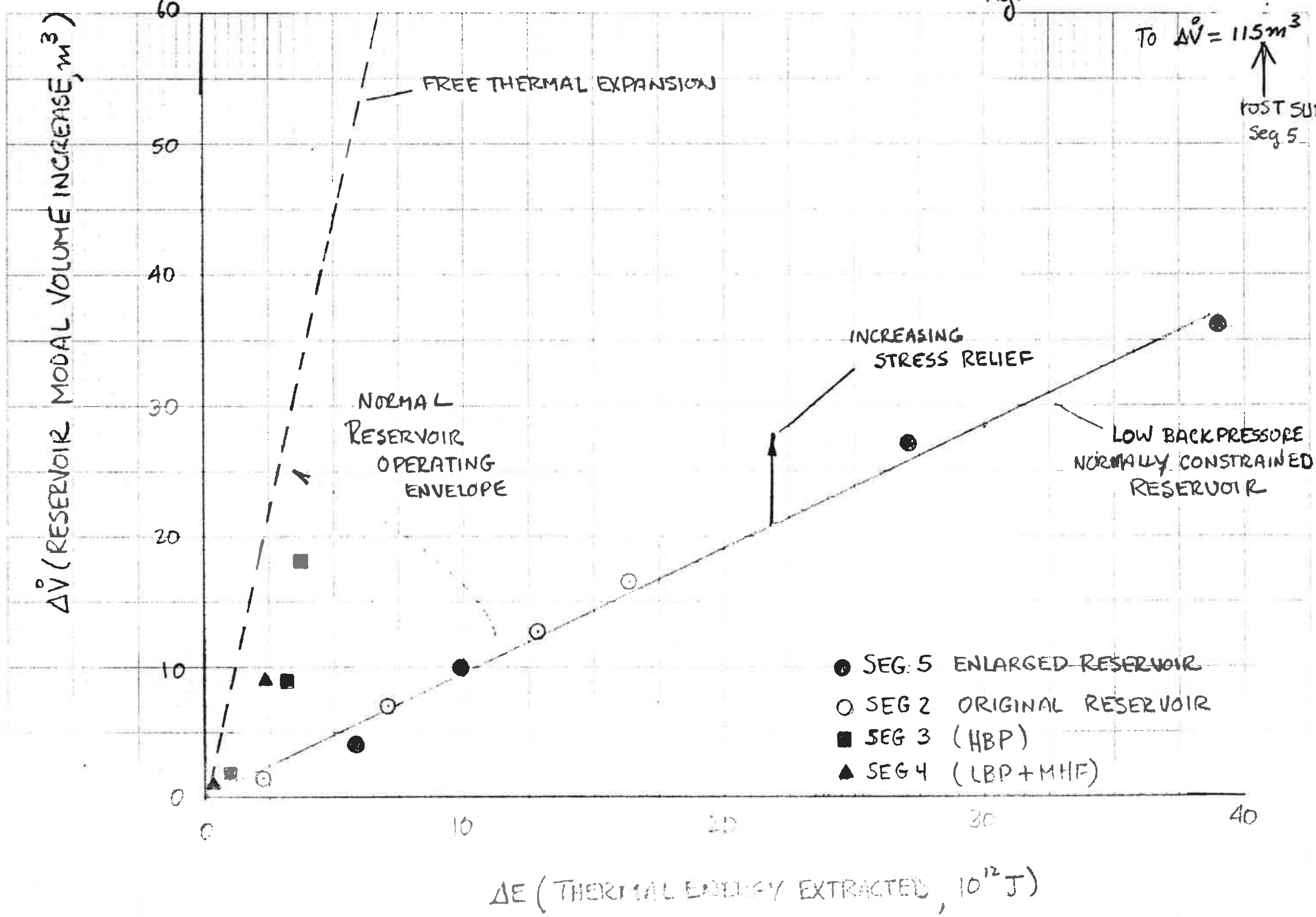
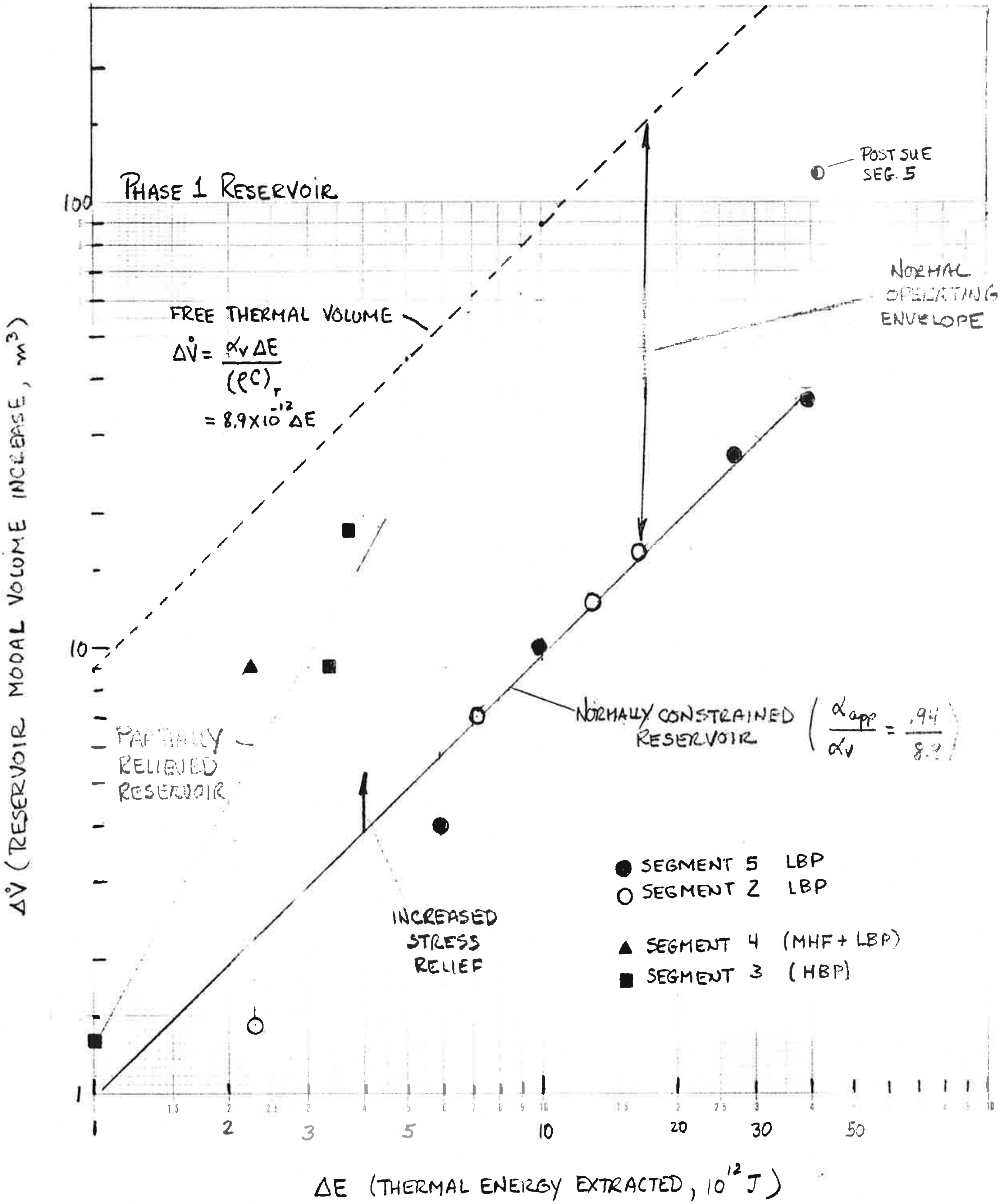
Fig. 1



To $\overset{o}{\Delta V} = 115 m^3$
POST SUE Seg 5
FREE THERMAL EXPANSION
NORMAL RESERVOIR OPERATING ENVELOPE
INCREASING STRESS RELIEF
LOW BACKPRESSURE NORMALLY CONSTRAINED RESERVOIR
SEG 5 ENLARGED RESERVOIR
SEG 2 ORIGINAL RESERVOIR
SEG 3 (HBP)
SEG 4 (LBP + MHF)
$\overset{o}{\Delta V}$ (RESERVOIR MODAL VOLUME INCREASE, m^3)
0
10
20
30
40
50
60
0
10
20
30
40



PHASE 1 RESERVOIR
POST SUE SEG. 5
NORMAL OPERATING ENVELOPE
FREE THERMAL VOLUME
$\Delta\mathring{V} = \frac{\alpha_v \Delta E}{(\rho C)_r}$
$= 8.9 \times 10^{-12} \Delta E$
NORMALLY CONSTRAINED RESERVOIR
PARTIALLY RELIEVED RESERVOIR
INCREASED STRESS RELIEF
SEGMENT 5 LBP
SEGMENT 2 LBP
SEGMENT 4 (MHF + LBP)
SEGMENT 3 (HBP)
$\Delta\mathring{V}$ (RESERVOIR MODAL VOLUME INCREASE, m^3)
ΔE (THERMAL ENERGY EXTRACTED, 10^{12} J)

Fig 2

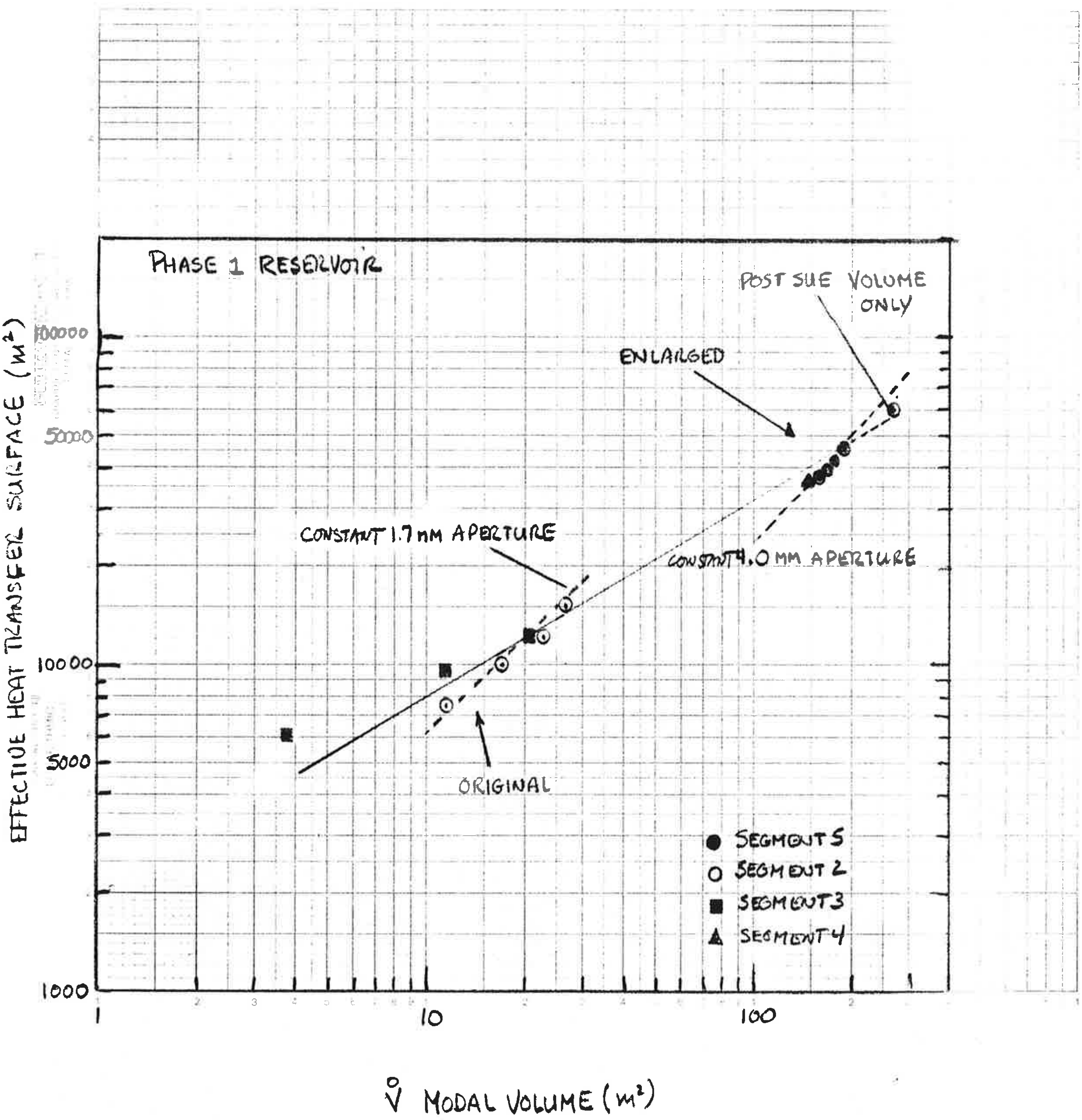

PHASE 1 RESERVOIR
POST SUE VOLUME ONLY
ENLARGED
CONSTANT 1.7 MM APERTURE
CONSTANT 4.0 MM APERTURE
ORIGINAL
SEGMENT 5
SEGMENT 2
SEGMENT 3
SEGMENT 4
EFFECTIVE HEAT TRANSFER SURFACE (m^2)
100000
50000
10000
5000
1000
1
10
100
$\mathring{V}$ MODAL VOLUME (m^3)

Fig 3